STATE OF THE ART IN SEISMIC VULNERABILITY

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1. INTRODUCTION

The seismic phenomenon has lived with the humans since the start of the times but it has been only over the last century when we have begun to understand what earthquakes are and what causes them. Now, we admit that earthquake occurrence is not random but driven by natural forces due to the evolutionary process of the planet we live on. Although we have started to develop predictive methods, which reduce the uncertainty about, where and when the next destructive earthquake will happen we have to be aware that the continuous growth of the population is related to a continuous growth of the size and number of villages, towns and cities across the globe. For this reason we still have to increase our effort in reducing the losses due to these earthquakes and one of the key points is the evaluation of the vulnerability.

Vulnerability studies are carried out prior to an earthquake for the purpose of assessing the need to strength essential facilities and structures again future earthquakes. The most of the buildings, also those built without seismic code, have an inherent lateral strength which may be sufficient for the building to resist moderate sized earthquakes with an acceptable degree of damage. If the damage is acceptable or not it will vary according to the importance of the building, its use and the owner's requirement. Anyway we should be able to estimate a probabilistic measure of the damage to the building resulting from a given ground motion.

The vulnerability of an element is defined as the probability that the said element will sustain a specified degree of structural damage given a certain level of ground motion severity.

Vulnerability analysis can be carried out to buildings, essential facilities, lifelines, etc, and, so, depending on the element whose vulnerability is going to be assessed, then different approach can be used. Mainly, we can distinguish between two different methods. The probabilistic approach (also called observed vulnerability) is, mainly, used when a group of buildings are studied and it is based on statistic of past earthquake damage. On the other hand the deterministic approach (also called predicted vulnerability) can be used in dealing with single structural units (Sandi, 1982) and it refers to the assessment of expected performance of buildings based on calculation and design specifications.

The vulnerability is usually represented in terms of either Damage Probability Matrices (DPM) or Vulnerability (Fragility) Curves. While the DPM describe a discrete relationship between the probability of damage occurrence and increasing ground motion severity, the fragility curves do it in a continuous way.

Also in the deterministic approach a performance point (spectral acceleration, spectral displacement) is derived by the intersection of the 'demand' (spectral acceleration) on the building created by the ground motion and the 'capacity' (spectral displacement) of the building in terms of a response or capacity curve. This performance point is used in conjunction with fragility curves in order to assess the percentage of damage.

Mainly, in order to assess the losses due to ground shaking over a distribution of buildings we need (Coburn and Spence, 2002):

1. A means of specifying the earthquake hazard
2. A classification of the building types or other facilities into different types whose performance in earthquakes is likely to be similar both in nature and degree.
3. A method of defining loss so that extent of loss to a particular building or population of buildings can be quantified.
4. A means of estimating the distribution of losses to each building type for each discrete level of ground shaking (if intensity scales are used) or as a function of ground shaking (if a continuous parameter of ground shaking is used).

Now we will describe both vulnerability assessment approaches.

2. PROBABILISTIC METHODS.

Vulnerability curves consist of a set of relationships between ground motion and probability of exceedence of damage. Each threshold of damage of damage limit-state has its corresponding relationship. The shape of the vulnerability curves is different for different structural type due to variations in their rate of accumulation of damage with increasing ground motion.

There is a large variation in the parameters used to represent the expected damage and ground motion severity. In the case of most existing relationships however, the ground motion is expressed in terms of an intensity value and the damage as a ratio of the expected maximum loss (ranging from 0 to 1, for example). Each vulnerability curve therefore describes the probability that a specified level of damage (d) will be equalled or exceeded ($D \geq d$) at a given ground motion value (Y), as specified in the equation:

$$P(D \geq d \mid Y) = 1 - F_{D|Y}(d \mid Y)$$

If p_{ik} is the probability that a structure is in damage state d_i for a given ground motion y_k, then:

$$P_{ik} = P[D = d_i \mid Y = y_k] = \sum_{j=1}^{n} p_{jk}$$

If P_{ik} is evaluated by varying *k*, (i.e. the ground motion severity), whilst keeping *i* constant (i.e. a constant level of damage), then a fragility curve can be plotted for the damage state *i*.

Many different vulnerability curves have been derived by government agencies and research institutes around the world in order to assess the seismic risk associated with different classes of structure.

According to the source of the statistical damage data used for the curve generation, we can distinguish between four generic curve types:

1. Empirical curves, which are based on observed earthquake damage data.
2. Judgment curves, which are based on expert opinion.
3. Analytical curves, which are based on analytically simulated damage data.
4. Hybrid curves, which are based on combinations of the above sources.

2.1 Empirical curves

Usually when an earthquake has happened, it is possible to get a distribution of the building damage with surveys. Then we can derive an empirical vulnerability curve with this information. Therefore, in the curve derivation, we are assuming that damage due to past earthquakes observed in the structures classified by type, will be the same in future earthquakes in that region and it will be representative of the vulnerability for areas with similar building stocks when subjected to similar size future events.

The format of this curves also depend on the parameter used to define the hazard. If the intensity, which is a discrete scale, is chosen then the most widely used form is the damage probability matrix (DPM). The DPM (Figure 1) shows the probability distribution of damage among the different damage states, for each level of ground shaking and defined for each separate class of building or vulnerable facility.

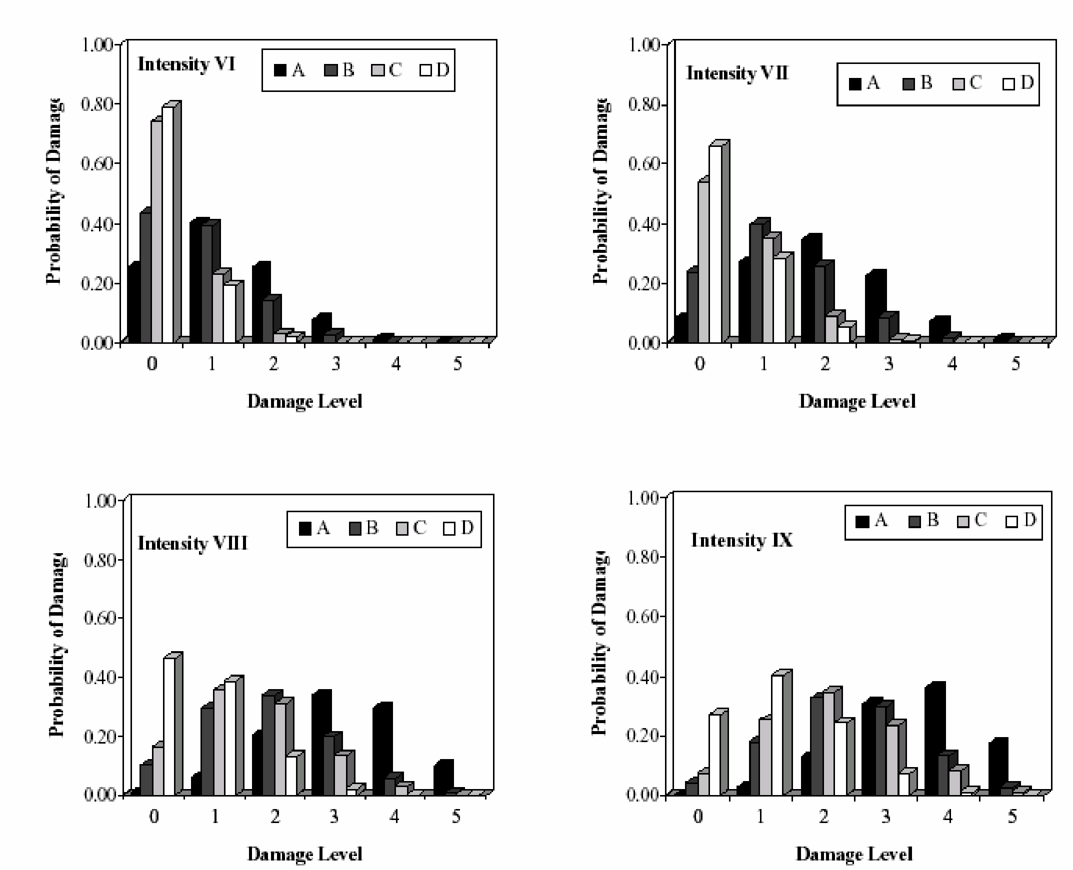

Figure 1. Example of DPM for A, B, C and D vulnerability classes according to EMS-92 (Chavez et al., 1998)

On the other hand if the hazard is defined in terms of an engineering parameter of ground motion as PGA, spectral acceleration, etc. similar information is usually presented as a continuous relationship.

The most important problem when deriving and applying these empirical curves comes from the fact that in the most of the cases they are derived from scarce observational data. This data often derives from a single location or earthquake event, so vulnerability curves are extrapolated from few points that only cover a limited range of ground motion values and usually there is a significant scatter of the points when compared to the curve.

The use of data from a single location may limit the use of the curve to that location due to the nature of the local building stock (composition and construction practices). That is, the curves will be appropriated for the building population of that location and maybe they could be used in other areas where we can assume a similar building population.

The most important advantage of this vulnerability curves, if based on a reliable and large quantity of data, are that they reflect real damage and can incorporate the effects on building response of factor such as material degradation, configuration and detailing arrangement, which are otherwise difficult to model.

Regarding the use of DPM showing the damage distribution, it is usually presented in the form of histograms. Braga et al. (1982) showed that the distribution of damage for well-defined classes of buildings tended to follow a pattern which is close to the binomial distribution. Using this form, the entire distribution of the buildings among the six different damage states D0-D5 could be represented by a single parameter (p) of the binomial distribution. This parameter can take any value between 0 (no damage, D0) and 1 (collapse, D5). In Figure 2 we can see the distributions generated for particular values of p. In this way, the definition of damage distribution in terms of p simplifies these damage definitions (replacing a six-parameter specification with a single parameter for each building class and level of ground motion) and provides a better basis for the use of limited damage data in generating distributions (DPMs or continuous vulnerability functions). Observations suggest a good fit between the binomial model and damage distributions of masonry building although other more complex building types may require another distribution. Spence (1990) and ATC-13 (1985) gave a similar characterization of damage distribution in terms of the beta distribution, which uses two parameters, and hence allow for more flexibility in the shape of the distribution to fit different circumstances.

Spence et al. (1999) obtained vulnerability curves for brick masonry buildings with data from several earthquakes worldwide an using normal cumulative distributions to define the shape of the curves and the PSI (Parameterless Scale of Intensity) to represent the ground motion. This PSI scale were derived in order to avoid the difficulties related to the macroseismic intensity scale, that is, its discreteness, the discrepancies between intensity assignation by different survey groups and the non real performance of different building types which intensity scales assume (Coburn and Spence, 2002). PSI scale is continuous and is based on the observation of damage distribution in buildings and their relative performance with respect to brick masonry constructions in the same area, and has the advantage of represent the comprehensive effects of ground motion, soil conditions and structural vulnerability. Likewise, vulnerability curves for other building types have been derived from their performance relative to brick buildings in surveys. With this vulnerability curves the proportion of buildings damaged to any particular damage or greater is given by the standard Gaussian distribution function.

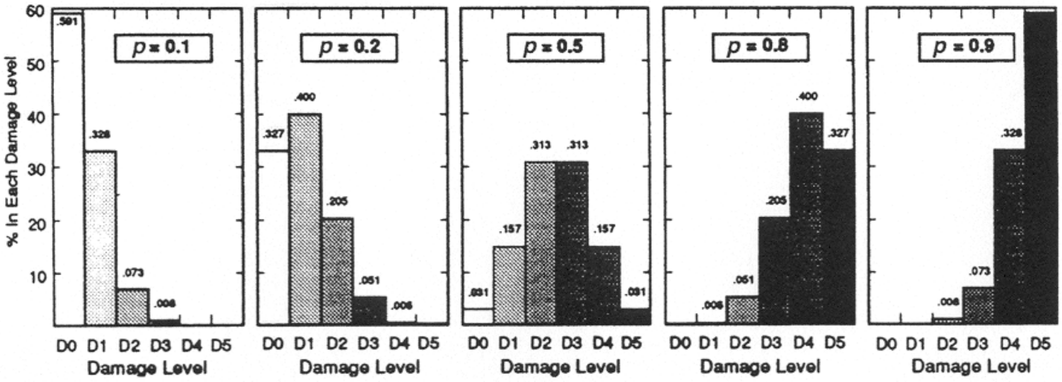

Figure 2. Theoretical distributions for each damage level D0-D5 defined by different values of binomial parameter *p*.(from Coburn and Spence, 2002).

As there is not any PSI attenuation function, PSI is related to other measures of ground motion as EMS scale, peak horizontal ground acceleration (PHGA) and mean response spectral acceleration (MRSA). For the instrumental parameters, the correlation coefficients are not high but it looks that MRSA is a better predictor of PSI than PHGA. (Spence et al., 1991)

Orsini (1999) also got vulnerability curves for different types of structure using building damage data collected after the Irpinia earthquake 1980. He introduces the use of the apartments as the structural damage unit rather than buildings, the PSI to represent the ground motion severity and the MSK scale to define the limit states.

Yamazaki and Murao (2000) also obtained empirical vulnerability curves with data from the Kobe earthquake using cumulative lognormal distribution functions to describe the shape of the vulnerability curves, the peak ground velocity as ground motion parameter and the AIJ classification of damage. The data was discretized according to structural type, age and height. As it was not available the same degree of accuracy in the ground motion distribution than in the distribution of building damage, they solved this problem using an iterative method for the vulnerability curve derivation. During the iterative process the PGV distribution derived by the authors is re-estimated using preliminary vulnerability functions. The new distribution for the ground motion parameter is then used to draw new vulnerability curves and the process of PGV res-estimation repeated.

2.2 Judgment curves

In this case vulnerability curves are obtained by means of expert opinion. That is, a group of experts (civil and structural engineers with proved experience in earthquake engineering) is formed. Each experts is asked to provide estimates of both the mean and the standard deviation of the building damage distribution expected to result from the occurrence of an earthquake of a given intensity. This predictions are fitted using probability distribution functions so it can be derived the probability of a specified damage state and plotted against the corresponding ground motion level. In this way a set of vulnerability curves and associated uncertainty bounds are derived.

This curves solved the problem associated with the scarcity of data, which appears in the empirical methods, and the curves can be easily made to include the factors affecting the seismic response of different structures.

ATC-13 and ATC-40 documents are one example of this kind of vulnerability curves contained in rehabilitation codes.

The same as in the empirical methods, vulnerability curves based on expert opinion should also strictly only be applied to the location for which they were created.

2.3 Analytical curves

Another way of solving the problems related with the scarcity of data is the use of analytical tools in order to simulate earthquake behaviour of any kind of structural model representing buildings. Then we can obtain a detailed set of statistical damage data in order to estimate vulnerability curves.

There is a lot of procedures for the analysis of a structures and its loading, ranging from traditional elastic analysis to non-linear time history analyses on 3D models of structures. According to the chosen procedure also different representation of the seismic hazard is needed (ground motion parameters, response spectra, earthquake time histories).

This means that for the same location and group of buildings, different research can obtained different analytical vulnerability curves with significance differences, in function of the chosen procedure. Anyway, the reliability of the curves have to be checked by means of post-earthquake damage surveys.

Examples of analytical vulnerability curve estimation can be seen in Onose (1984), Singhai and Kiremidjian (1997) and Mosalam et al. (1997). Onose use a reliability-based method, (analytical but including empirical features) for the assessment of reinforced concrete buildings but it makes many assumptions and requires prior knowledge of the distribution of building resistance in the assessed area. Also he uses a ductility factor as damage indicator which it is not suitable because it is not unable to account for failures caused by damage concentration at the storey level. Singhai and Kiremidjian derive analytical curves using non linear time history analysis applied to model frames of low-, medium- and high-rise reinforced concrete bare frames in California, USA. The ground motion is represent by the average spectral acceleration ordinate in the period ranging from 0.1-0.5s, 0.5-0.9s and 0.9-2.5s. The shape of the curve is described by a lognormal distribution. However only the vulnerability curves derived for low-rise frames are verified against the actual damage observations. Finally, Mosalam et al., compute analytical curves for the typical buildings in Memphis, USA (low-rise reinforced concrete frames with and without infill walls). In order to define the dynamic properties of the equivalent single degree of freedom (SDOF) systems, pushover analyses are carried out. Then using artificial earthquakes records from two different sources, vulnerability curves are derived by means of the results of the time-histories analyses carried out on the equivalent SDOF system. The ground motion parameter used is the peak ground acceleration and the maximum inter-storey drift ratio is used as the damage state indicator.

2.4 Hybrid curves

These curves are usually derived from combinations of observed damage statistics with either expert opinion and/or inferences made from experimental tests and/or analytical simulations. Some examples of these curves appear in the ATC-40 and HAZUS99 documents. Also, Singhai and Kiremidjian (1997) got hybrid curves because they include observational data into the derived analytical curves. An important part of this method is the weighting system used to take into account the realibility of the different data sources, as for example the Bayesian updating technique in Singhai and Kiremidjian (1997).

3. DETERMINISTIC METHODS.

Advantage of numerical methods of vulnerability assessment gives an opportunity of multivariant modeling of behaviour of buildings and structures as much as possible approached to the real conditions. The vulnerability models are based on detailed numerical analysis (linear, non-linear, static, dynamic) of a given structure.

Appropriate response of the structure allows to evaluate damage degree and repair costs. The vulnerability function can relate damage degree to inter-story drift, or to static and dynamic loads.

The following procedures of analysis are used as the basis of vulnerability assessment: linear analysis using spectral response curve; linear time history; nonlinear ("push-over") analysis force controlled and displacement controlled; nonlinear time history analysis. On the basis of calculation results – type and quantity of damages in structural elements, change of dynamic parameters of a building the expected damage grade and possible losses are estimated. All these procedures have different possibilities and differently approach to the real behaviour of a structure.

Currently, it has been done a great effort in order to include the most recent state of the art in loss estimation studies into a seismic risk tool for USA. This tool is called HAZUS and it can be considered as a deterministic (predictive) method of loss estimation based on recent perfomance-based procedures for the design of new buildings and for retrofitting existing buildings. For any individual building, these procedures enable levels of earthquake ground motion to be defined which correspond to a range of post-earthquake damage states, from undamaged to complete collapse. The use of such procedures is as applicable to evaluation as it is to design: that is, they can be used for assessing the probable state of an existing building after a given earthquake motion as well as for designing new (or strengthening existing) buildings.

The main point of HAZUS is a process for developing vulnerability or fragility curves for buildings and other facilities, to estimate the losses from ground shaking, which has been used to define likely losses for a range of different building types found in the United States. Altogether it defines 36 different classes of buildings and many other facility classifications, distinguished according to age, height and level of seismic resistance designed for. For each building class a set of parameters defines the expected average earthquake capacity curve for the class. This curve, together with further parameters, then defines the displacement response to any given earthquake ground motion, resulting in an expected loss distribution for a typical population of buildings of any class.

In the HAZUS methodology the damage state of a building is taken to be defined by the interstorey drift ratio at the most deformed level of the building. Five damage states has been defined (none, slight, moderate, extensive and complete) with detailed descriptors of the state of damage which corresponds with each state for each class.

For a single building, and for any given earthquake ground motion, the interstorey drift is derived from the spectral displacement of the building as a whole in response to the motion. This spectral displacement, called *performance point* for the building, is defined by the interaction of the *demand* on the building created by the ground motion, and the *capacity* of the building in terms of a response or capacity curve, which is derived from the elastic response of a single degree-of-freedom system by taking account of the degradation of the building as shaking progresses. Both demand and capacity are defined by curves of *spectral acceleration* S_a against *spectral displacement* S_d, and the performance point *(Sa, Sd)* is taken to be at the intersection of these two curves.

The capacity curve (also known as a push-over curve) is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement (i.e. a force deflection plot). It is derived from a plot of static-equivalent base shear versus building (e.g. roof) displacement. In order to facilitate direct comparison with earthquake demand (i.e. overlaying the capacity curve with a response spectrum), the force (base shear) axis is converted to spectral acceleration and the displacement axis is converted to spectral displacement. Such a plot provides an estimate of the building's "true" deflection (displacement response) for any given earthquake response spectrum.

The building capacity curves are developed from a nonlinear static (pushover) analysis of the building that conform essentially to the methods of NEHRP Guidelines (or ATC-40). Certain structural analysis software automatically convert pushover curves to capacity curves.

For each building type the capacity curve for *Sa* versus *Sd* has an initial linear section where the slope depends on the typical natural frequency of the building class, and rises to a plateau level of *Sa* at which the maximum attainable resistance to static lateral force has been reached.

On the other hand, the demand curve derives form a damped elastic spectral response curve built from spectral parameters of the ground motion, as modified according to soil type. This is done by incorporating spectral reduction factors to account for the increased hysteretic damping as the building shift from elastic into inelastic response.

Finally the damage distribution is obtained by means of the spectral response of the building at the performance point for the standard building of that class used in conjunction with a set of four fragility curves for that class, which estimate the probability of any particular building being in each of the four damage states after shaking at any given spectral response level. Each of these curves is assumed to be lognormal in form, and is defined by two parameters: a *median value* and a *coefficient of variation*. The most of the buildings use the spectral displacement as spectral response but some classes of facilities and some building elements and equipment are taken to be damaged as a result of the spectral acceleration rather than the spectral displacement.

4. VULNERABILITY INCORPORATION IN SEISMIC CODES AND MANAGEMENT STRATEGIES

One of the widely used mitigation tools is the incorporation of the seismic provisions in building codes. By using codes to effect seismically resistant construction, a community can replace the bulk of its building stock over time with one less vulnerable to damage and collapse. Because the approach does not restrict or modify land-use patterns, and because it is relatively inexpensive when applied strictly to new constructions, building codes are perhaps the most popular of implementations options, and sometimes thought as the sole tool of mitigation. Seismic building codes do not govern every aspect of a community's building stock, but typically focus on specific parts of specific building types.
Codes can not serve as a substitute for seismic engineering expertise, and indeed require skill and judgment on the part of their executors.

Although in theory codes can be written so that all buildings in a community are completely built to seismically resistant standards, in practice their application is more selective. Because the application of building codes involves a cost in money and effort, prioritisation is necessary, and not all the buildings and not all the parts of buildings are treated equally. First and foremost, the seismic portion of a building code typically deals with the building's so-called structural components (i.e. the frames, columns, beams, and load-bearing wall whose failure can lead to building collapse and consequent loss of life). Moreover, the structural components are not necessarily intended to survive a strong earthquake unscathed: if the component is damaged but does not collapse, the code is considered to have done its job.
Besides making a distinction between structural and non-structural components, building codes distinguish in terms of building use. In general, structures that serve critical functions (e.g. hospitals, schools,…) are held to a higher standard than less occupied buildings. These distinction again reflect the life safety focus of most codes and the great cost of more broad-based mitigation.

In summary, building codes for new construction, although relatively popular and potentially powerful, are no the best tool, they generally cover only structural collapse, they still require some level of seismic engineering knowledge in order to work well, and they must be enforced.

Eurocode 8, for example, adopts a force-based design philosophy focused on seismic force demands and member strength capacities, and it can be considered to be the state-of-the practice. It principally adopts a one-level design procedure, primarily to satisfy a “life-safety” objective. This implies that the structure may be damaged, but it must not collapse in order to prevent loss of life. This is similar to the US Uniform Building Code among others.

Consistent with the force-based design philosophy, Eurocode 8 requires that members of buildings be sized for strength and ductility. The elastic seismic force demand of every structural member is reduced by the same global structural behaviour factor (q) .

In the design process for strength a classification of structural regularity, a seismic structural modelling and analysis and a strength design for the ultimate limit state have to be considered.

Structures are classified as either regular or non-regular based on regularity criteria both in plan and elevation. This classification influences the value of the behaviour factor and determines the type of structural model and method of seismic load analysis.

Also Eurocode 8 reflects the importance of seismic evaluation and retrofit of existing structures. This is important because seismic loading may not have been considered in the design and construction of many old structures. Second, present knowledge with respect to seismic hazard and occurrence of more recent earthquakes has increased the awareness of seismic risk to existing structures and created the need to retrofit vulnerable structures. The complete process embraces data and information collection, seismic evaluation, seismic retrofit strategy and scheme design and detailed seismic retrofit design.

Anyway, Lubkowski and Duan (2001) think that this approach is not a satisfactory methodology for seismic assessment and retrofit of existing structures.

The authors suggest to learn from the US experience and philosophy. In that way, the United States has adopted the performance-based and displacement-based philosophy included in the FEMA 273 and ATC 40 documents. These documents show that difficulties are better overcome by quantifying the ductility (inelastic deformation) capacities of the existing structural components using displacement-based parameters established from laboratory component test data and then assessing the seismic deformation demands, namely by adopting a displacement-based methodology.

These guidelines (NEHRP Guidelines for the Rehabilitation on Buildings – FEMA 273) use the capacity spectrum method to estimate the expected damage state of a structure. This method is based on the relationship between spectral acceleration and spectral displacement, which is used to represent the earthquake demand on the structure

Recent earthquakes have demonstrated the complex interaction that exist between the various components of the infrastructure of modern urban environments. The loss of a single bridge, dam, power substation, or telephone exchange can have far-reaching secondary effects. The ability to anticipate these effects would provide a basis for earthquake hazard mitigation.

The HAZUS methodology, previously explained, was developed by the Federal Emergency Management Agency (FEMA) in the United States in order to realize these objectives.

Finally current trends in the development of new building codes have all embraced the concept of performance-based design, and conceptual frameworks of that approach have been developed in SEAOC Vision 2000, FEMA 273, and EERI (1998)

5. VULNERABILITY IN SEISMIC RISK STUDIES

Probabilistic methods of vulnerability estimation (empirical and judgement curves mostly) have been used frequently in the most of the seismic risk studies due to its simplicity although nowadays numerical methods (analytical and hybrid and deterministic) have increased their use just alone or as a complement of the empirical methods.

Some of the vulnerability curve estimation methodologies have been discussed previously but we want also to remark some recent studies on seismic risk with improved vulnerability methods.

Wen and Huzian (2000) used an analytical method of vulnerability analysis to estimate the vulnerability of multistory or high-rise reinforced concrete. Using relationships among key point in parameterless pushover curves and the seismic design level then they transform the parameterless pushover curves to general pushover curves and then to spectral capacity curves using the simplified nonlinear static analysis method. These curves are used to estimate the seismic vulnerability of multi-storey or high-rise reinforce concrete. The authors say that the method overcome the earthquake data limitation on vulnerability estimation. In summary, after the estimation of peak response of buildings for a given level of spectral demand, fragility curves are established, and then the probability of earthquake damage to existing buildings in China is predicted. As a conclusion the authors state that the method allows for incorporation of important ground motion characteristic, including site/soil amplification effects, type of earthquake, frequency content and the structural behaviour of buildings. Also it overcomes drawbacks and logical random-error in damage estimation, subjective intensity assessment, discrete values of intensity and actual damage data limitation on seismic evaluation by empirical approach.

Ordaz et al. (2000) use the acceleration spectra and general structural characteristic to estimate the maximum inter-storey drift ratio by means of a simplified model. The approach uses displacement-based vulnerability functions to estimate the damage ratio from the maximum inter-storey drift. The use of spectral acceleration as seismic motion and maximum inter-story drift as damage level in the structure is because there are an important number of studies that conclude that this parameter has the best correlation with structural damage. The method is partly analytical and partly empirical because the reference spectra are computed using semi-empirical spectral attenuation laws, some of which were derived from acelerographic information recorded in Mexico during the past 35 years.

Yamaguchi and Yamazaki (2000) use the damage surveys conducted by groups of researchers and engineers after the 1995 Kobe earthquake to develop fragility curves. The buildings were classified in five categories and a further classification was done for wood-frame and reinforced concrete buildings in terms of construction period (three periods for reinforced concrete due to the revisions of the seismic code and five for wood-frame buildings- approximate by every five years). Using the strong ground motion indices (PGA, PGV, SI, JMA Intensity) and the damage ratio, fragility curves were constructed. The cumulative probability of occurrence of damage is assumed to be lognormal for PGA, PGV and SI and normal for JMA Intensity. The authors conclude that the accuracy of the proposed fragility curves can further be improved by introducing building damage data of neighbouring cities and the result of analytical studies.

Okada and Takai (2000) propose vulnerability functions on five damage degrees in the MSK scale, based on the data obtained by the building damage investigation in the Kobe city in the 1995 Hyogo-ken Nanbu earthquake. The damage rate of buildings is given in terms of a Gaussian distribution.

Mucciarelli et al. (2001) use the HVSR technique (microtremor measurements on the floors of the existing buildings) to estimate the interstorey drift defined as the horizontal displacement between two floors (U_n and U_{n-1}). In the estimation the horizontal-to-vertical ratio of weak motion and microtremors is used to evaluate the acceleration transfer function at the n-th floor and the site amplification. Then using that formula the expected maximum deformation of the building can be proposed and compared with the expected earthquake spectrum on the site so a degree of vulnerability can be associated by means of the comparison of the highest peaks of the two curves. The methodology provides an alternative, promising tool towards a quick an reliable estimate of seismic vulnerability.

Pinho et al. (2002) propose a simplified approach for cases in which the available data on the soil conditions and building stock is limited and the computational complexity of the Capacity Spectrum Method is not justified. Their approach retains the elements of the natural period of vibration of structures and structural displacements as most suitable indicator of damage. They simplify the HAZUS procedure taking into consideration the relationship between the different qualitative damage states usually defined in loss estimation studies and interstorey or global drifts (displacements as a proportion of storey or total height) in buildings. The authors use empirical relationships between the period of vibration and building height to plot *capacity curves* for different drift levels in terms of period and displacement. The intersection between any given displacement spectrum chosen to represent the demand and damped to the appropriate level, and the drift capacity curves indicate the periods that mark the boundaries of the various limit states. These periods can then be transformed into their equivalent heights using the previously mentioned period-height relationships, and plotted across a cumulative distribution function of buildings with height to find the proportions of the exposed building stock failing each limit state.

Finally Carvallo et al. (2002) presents a classification of residential buildings in Portugal into typological classes, which vulnerability is characterized through a HAZUS methodology. The housing stock was classified into forty-nine distinct types, inserted in seven typological classes, taking into consideration the construction epoch, the resisting element and seven typical values of the factor number of floors. The capacity curves were derived from estimates of acceleration and displacement values corresponding to yield and ultimate capacity (in terms of strength and ductility) of typical buildings. Both these values and the global drift limit values were preliminary established by adjusting with HAZUS building types. The author conclude that this curve should be considered preliminary and should be calibrated through analytical and experimental studies.

6. CONCLUSIONS

When performing vulnerability analysis and in absence of statistical data about vulnerability of some types of widespread buildings, unique structures, historical monuments etc, the development of numerical methods and approaches of evaluation and identification of vulnerability grade is shown as an important tool for different purposes connected to risk assessment from natural disasters.

For adequate vulnerability assessment the design model of a building should take into consideration the soil-structure interaction, spatial effects and real structural features including existing damages.

Probabilistic (empirical and judgment vulnerability methods) are the simplest but they need huge damage database from old earthquakes with different size and in different regions and they are valid if they are applied in locations with the same building characteristic as the database. Anyway it is not so clear if the damage from moderate earthquake can be extrapolated to higher earthquakes.

Currently the most recent vulnerability method applied in loss estimation studies (HAZUS approach) involves the use of numerical methods (deterministic) by means of the Capacity Spectrum Method and the damage state of a building is taken to be defined by the interstorey drift ratio at the most deformed level of the building. This parameter has been confirmed as having the best correlation with structural damage. This method has its power in the use of as much as possible information on soil conditions and building stock, but in those cases in which this information is scarce, a simplified approach (with less computational complexity), as demonstrated by Pinho et al. (2002) looks to be valid.

Anyway, these deterministic (predictive, theoretical or numerical) methods have to be calibrated with damage data from old earthquakes if possible and future earthquakes once they have happened.

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